

I. INTRODUCTION

A. Background

The Large Deployable Reflector (LDR) is a system concept for a dedicated, orbiting, submillimeter/far infrared, astronomical observatory which has been studied by the National Aeronautics and Space Administration (NASA) since the late 1970's. Three Asilomar LDR workshops have been held to bring a wider range of expertise, both scientific and technical, into the LDR planning, definition, and critical technology development.

The first workshop, which is now called Asilomar I, was sponsored by the Office of Aeronautics and Space Technology (OAST). It was held in June 1982 at the Asilomar Conference Center at Pacific Grove, California. The purpose of the workshop was to define the science requirements, to derive the system functional requirements from the science requirements, to discuss the system concepts that would meet the functional requirements, to carry out a technology assessment, and to recommend a future course of action for LDR. The degree to which the workshop achieved its objectives can be demonstrated by noting that the science objectives, functional requirements, and system concept have survived from 1982 to the present with only minor, evolutionary changes.

The second workshop, Asilomar II, was held in March 1985; it was jointly sponsored by the Office of Aeronautics and Space Technology and the Office of Space Science and Applications (OSSA). Its purpose was to assess, identify, and prioritize the LDR technology issues, and to develop a technology development plan. This technology plan ultimately became the basis for the FY'88 Civil Space Technology Initiative/Precision Segmented Reflector (CSTI/PSR) program at Jet Propulsion Laboratory (JPL) and Langley Research Center (LaRC), and has strongly influenced the CSTI sensors program.

The third Asilomar conference was held in September 1987 and is the subject of this report. Its purpose was to review the latest system concepts for LDR, update the science requirements, and assess the status of the technology development that was recommended at Asilomar II. The technology development assessment included ongoing work within NASA, the Department of Defense (DOD), and various universities. Problem areas and technologies not being adequately addressed were to be identified and prioritized. In particular, the CSTI program in Sensors and Precision Segmented Reflectors was reviewed for appropriateness and progress relative to LDR technology needs.

B. Asilomar III Organization

The third Asilomar workshop was sponsored jointly by the Office of Aeronautics and Space Technology and the Office of Space Science and Applications. Attendance was by invitation, and included approximately 110 participants from NASA, industry, and universities, as well as a participant from the European Space Agency's Far Infrared and Submillimeter Space Telescope (FIRST) study group.

The workshop format alternated between panel working sessions of 10 to 20 people, and plenary sessions where the panel conclusions were presented to all participants. There were five technology panels: Controls and Pointing, Reflector Panels and Materials, Structures, Receivers and Cryogenics, and Optics and Systems. In addition, the LDR Science Coordination Group (SCG) was in attendance with its membership spread among the five technical panels.

The final agenda for the Asilomar III Workshop is shown in TABLE 1. The first two plenary sessions presented overview papers to bring all of the participants up to the same level of understanding concerning the LDR program and its status. This was followed by the first panel working sessions, at which technical papers were presented on specialized topics. The objective here was to assess the status of ongoing LDR-related technology in the areas represented by the five panels. This was followed by a plenary session at which a summary was presented by each of the five panel chairmen. The final working session of the panels discussed problem areas, technology voids, and suggested prioritized new thrusts. The summaries of the chairmen were again presented in a plenary session on the final day of the meeting.

TABLE 1. Asilomar III Final Agenda

Monday, September 7th		
1500	Asilomar check-in	(Administration Building)
1530-1800	Conference Registration and Reception	
		(Nautilus/Triton Rooms)
1630-1730	Meeting of Chairmen	
1800-1900	Dinner	
1900-2000	Plenary Session	(Nautilus Room)
	Welcome	Paul Swanson
	Procedures	Pat McLane
	Opening Remarks	Paul Swanson
	Lightweight Reflector Panels	Bob Freeland
		Paul McElroy

TABLE 1. Asilomar III Final Agenda (continued)

Tuesday, September 8th		
0830-0850	Plenary Session	(Nautilus Room)
	Opening Remarks	Sam Venneri (NASA)
		Don Rea (JPL)
0850-0930	LDR Baseline Concept	Bill Alff (LMSC)
0930-0950	SCG Report	Peter Wannier (JPL)
0950-1010	Submillimeter Explorer	Chas Beichman (JPL)
1010-1030	Break	
1030-1100	SIRTF, SOFIA, ISO	Mike Werner (ARC)
1100-1120	HST Metering Truss	Tom Golden (BAC)
1120-1140	CSTI/Precision Reflectors	Gene Pawlik (JPL)
1140-1200	CSTI/Sensors Program	Jim Cutts (JPL)
1200-1300	Lunch	
1300-1700	Panel Sessions / Technical Papers	
	Controls and Pointing	Marlin Room
	Panels and Materials	Surf and Sand Room
	Structures	Nautilus Room
	Optics and Systems	View Point East Room
	Receivers and Cryogenics	View Point West Room
1700-1800	Social	
1800-1900	Dinner	
1900-2000	Special Plenary Session on	Aden Meinel (JPL)
	Balloons and Precursors	Peter Wannier (JPL)

Wednesday, September 9th		
0815-1200	Plenary Session	(Nautilus Room)
	Panel Chairmen Summary Report on Status of ongoing technology development and present state of the art regarding LDR technology	
1200-1300	Lunch	
1300-1700	Panel Sessions / Technology Assessment	
1700-1800	Social	
1800-2000	Banquet	
	Speaker: Jerry Nelson, "The Keck Telescope"	

Thursday, September 10th		
0815-1200	Plenary Session	(Nautilus Room)
	Panel Chairmen report on problems, suggested plans and new thrusts.	
1200-	Check out / End of Workshop	
1200-1300	Chairmen meet to discuss writing of final report.	

C. Report Organization

This report on the Asilomar III LDR workshop nearly parallels the workshop agenda. Section II gives an overview of the LDR program, while Section III presents an account of programs and missions closely related to LDR. The summaries of the technical panel chairmen are given in Section IV for each of the five technical panels. Section V presents the concerns of the Science panel as determined by their participation in the five technical panels. Some of these concerns overlap those presented in Section IV, but the perspective is different. Section VI presents a synopsis of the workshop recommendations. Elaboration of these ideas for each of the technical panels can be found in Section IV under the subsections dealing with technology development recommendations. Finally, abstracted summaries of the individual papers presented during the technical panel working sessions are collected in the Appendix.

II. THE LDR PROGRAM - AN OVERVIEW

The Large Deployable Reflector is to be a dedicated, orbiting, astronomical observatory. It will operate as a diffraction-limited telescope in the wavelength region of 30 to 1000 microns where the Earth's atmosphere is almost completely opaque. It is presently a pre-phase A study carried out by the Jet Propulsion Laboratory and sponsored by the NASA Office of Space Science and Applications. The science rationale and requirements have been defined by the LDR Science Coordination Group and are presented in a 1986 report [5]; the current reference concept for LDR is discussed next.

A. Reference Concept for LDR

The reference concept for LDR has evolved since its introduction more than a decade ago. New opportunities, capabilities, and requirements have ensured this process. The current reference concept, which was presented at an early plenary session of the Asilomar III meeting, is summarized in a report [6] prepared by the Lockheed Missiles and Space Company (LMSC). It examined three previous studies -- one each by LMSC [7], the Eastman Kodak Company (EKC) [8], and the Jet Propulsion Laboratory [3], and chose the best features of these, subject to the constraint that the cost be minimized. The availability of the Space Station had an early impact on the requirements, but other drivers included the introduction of 2-stage optical designs, the decrease in the instrument count from eight to four, and the potential removal of the requirement for a light bucket mode of operation. The current LDR system requirements are summarized in TABLE 2.

TABLE 2. LDR System Requirements

PARAMETER	REQUIREMENT
Primary Mirror:	
Diameter	20 m
Temperature	< 200 K
Temperature Uniformity	<1 K
f/number	0.5-0.7
Secondary Mirror:	
Diameter	open
Temperature	< 125 K
Optical Form	2-stage on-axis
Field of View	> 3 arc-minutes
System f/number	≈10
Diffraction Limit	30-50 μm
Maximum System Emissivity	5 %
Pointing: Accuracy	0.1 arc-seconds
Stability (Jitter)	0.02 arc-seconds
Slew Rate	20 degrees/min
Scan Rate	1 degree/min
Tracking Rate	0.2 degrees/hr
Chopping: Frequency	2 Hz
Amplitude	1 arc-minutes
Duty Cycle	> 80 %
Sun Exclusion Angle	90 degrees
Earth Exclusion Angle	30-45 degrees
Number of Instruments	4
Useful Life	20 years
Refurbishing Interval	1-3 years
Orbit: Altitude	≈700 km
Inclination	28.5 degrees
Number of Shuttle Loads	<2 equivalent

The present concept for LDR is that of a 20-meter aperture reflecting telescope, diffraction-limited in the range 30-50 μm . The primary reflector is made up of approximately 90 lightweight, hexagonal panels, each two meters in size. The panels are supported by a deployable or erectable truss backup structure and surrounded by a sunshield to keep direct solar radiation from the primary surface. The reference concept for LDR employs a two-stage optical design in which primary figure errors are compensated for by means of a closed-loop servo system that measures the wavefront error and quasi-statically controls individual segments in a quaternary mirror which is conjugate to the primary. The focal plane instrument package will be made up

of four instruments housed behind the primary vertex. The instruments will contain both direct detectors and heterodyne receivers, and will be cryogenically cooled to temperatures of 2 K and below.

Significant technical challenges exist in the areas of lightweight deployable structures, lightweight structural composite mirrors, and the control of pointing, vibration, and figure. The submillimeter heterodyne receivers are just emerging from the laboratory and heterodyne arrays have yet to be demonstrated. Cryogenic instrument coolers with lifetimes of 3 to 4 years are not yet available. The present LDR concept has served to define the technology that must be developed before the project can be started. Section IV discusses the present NASA technology efforts directed toward solving these fundamental problems.

B. A Tentative Schedule for LDR

FIGURE 1 shows a tentative schedule for LDR through the start of Phase C/D. This schedule is for planning purposes only and does not represent a NASA commitment to a project start at any particular time. The dark shaded arrows are funded activities in FY'88. The Science Coordination Group and the system definition are funded by the OSSA, while the telescope and sensor development are part of a more general technology development funded by the OAST. The Phase A study in FY'92 is dependent on many intangibles such as the overall NASA budget, new starts for AXAF and SIRTf, and the state of technology readiness of LDR in the early 1990's.

III. LDR-RELATED PROGRAMS AND MISSIONS

A. Civil Space Technology Initiative

Within the NASA Civil Space Technology Initiative (CSTI) are two programs of great importance to LDR. Plenary session presentations, which are briefly summarized below, were made on both of these programs.

1. Precision Segmented Reflectors (PSR)

The PSR effort is a joint project between JPL and LaRC under CSTI. The effort is managed by Code RM in OAST with a deputy manager from Code EZ in OSSA. The PSR technology program is a step in the development and validation of increasingly more precise segmented reflector technology that might ultimately be

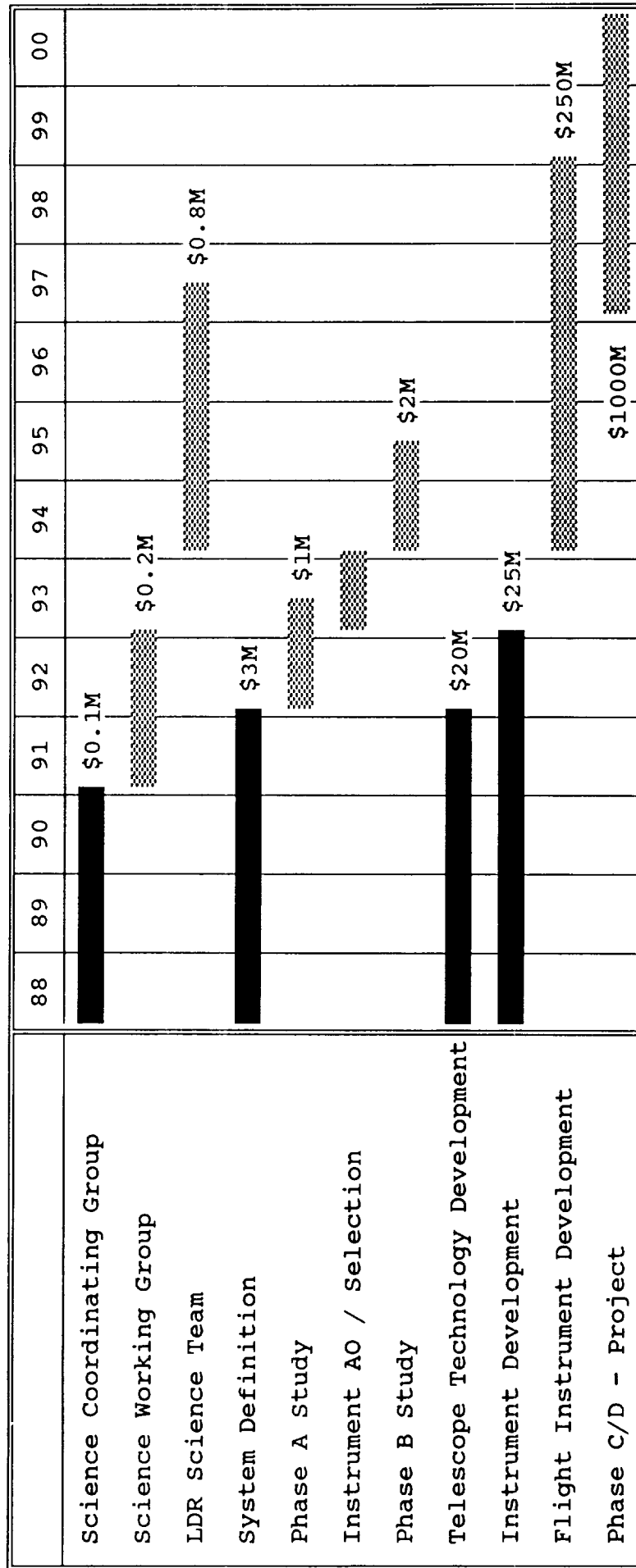


FIGURE 1. LDR Master Schedule to the Year 2000

used in space on projects such as the Large Deployable Reflector. These technologies include lightweight, structural composite panels, erectable and/or deployable space-like structures, advanced materials, and precision active control systems.

One of the objectives of the PSR program is to integrate the individual component technologies being developed within the program into a technology validation demonstration by the end of FY'91. The specific goal of the system is to demonstrate experimentally that a multi-segment, lightweight, low-cost reflector system can maintain a $\leq 5 \mu\text{m}$ rms overall surface accuracy when subjected to quasi-static thermal and mechanical disturbances representative of a space mission.

2. Science Sensor Technology

The science sensor technology program under the CSTI initiative involves work at a number of NASA centers in three main areas of relevance to LDR: submm receivers, direct IR detectors/arrays, and cryogenics.

In the submm receiver area, work is underway at CIT and JPL to develop high-sensitivity, space-qualifiable SIS mixers and arrays, improved antenna technology, and solid-state quantum-well devices for both local oscillator and frequency multiplier applications. Projects at LeRC and GSFC are aimed at bringing backward-wave oscillator, and CO_2 -pumped far-IR gas laser technology, respectively, to sufficient levels of maturity and ruggedness to satisfy LDR LO needs.

Direct detector work is supported under CSTI at Ames Research Center (ARC), JPL, and Marshall Space Flight Center (MSFC). The Ames program focusses on extrinsic silicon and germanium array technology, including advanced LDR-scale multiplexers and improved long-wave detector materials. At JPL, the technology of Ge:Ga blocked impurity band (BIB) detectors is under development. Arrays of superconducting bolometers are under investigation at MSFC.

CSTI cryogenics technology development is being supported at GSFC, ARC, JPL, and MSFC. The Goddard work emphasizes multi-stage Stirling-cycle coolers and supporting cryogenic engineering developments in regenerators and compressors. At Ames, (zero-g) dilution and pulse tube refrigerators are under development, as is a concept for a 2 K high-capacity closed-cycle cooler. The JPL work includes sorption coolers for a range of temperatures, and research into electrostatic separation of fluids for dilution refrigeration. Work on a ^3He - ^4He cooler, microchannel fountain-effect pump, and recuperative heat exchanger is underway at MSFC.

B. Missions

Presentations on the status of several funded or potential missions were made at Asilomar III plenary sessions and panel meetings. These talks discussed science and/or technology of direct interest to LDR; topics included the NASA Hubble Space Telescope (HST), the ESA Infrared Space Observatory (ISO) and Far Infrared and Submillimeter Space Telescope (FIRST), and the NASA Space Infrared Telescope Facility (SIRTF), Submillimeter Explorer (SMME), and Stratospheric Observatory for Infrared Astronomy (SOFIA). Since reports have been written on all of these missions, their details will not be pursued here. There was also a special evening session to discuss ballooning as a means for doing precursor science experiments. A technical paper discussing one of these, a proposed three-meter balloon-borne telescope, is included in Section F of the Appendix.

Although the spectral range of interest to these projects or proposals may overlap to varying degrees, all have significantly different performance characteristics. It is these attributes which must be traded against the science return and technology capabilities to determine those which should be pursued, and at what level. LDR stands to gain from these other projects in several important ways: general space telescope technology, science instrument development, and precursor science.

All of the missions require science instrument development which will greatly aid in defining the technology directions to explore for the LDR instrument complement. The SIRTF project, for example, is developing direct detector technology, which will benefit LDR, as well as an on-orbit superfluid helium transfer capability for stored cryogenics. As these instruments are developed, it is imperative that they be tested in a flight-like environment, but it is equally important that they also make relevant precursor science measurements. Balloon, aircraft (SOFIA), and low-cost spacecraft (SMME) missions provide a logical progression in reaching this objective, and in refining the system requirements for LDR.

IV. TECHNOLOGY PANEL REPORTS

This section contains the summary reports written by the chairmen of the five Asilomar III technical panels. The summaries follow the following general outline: an introduction, with some brief comments on changes since Asilomar II; an identification of technologies the panels felt were critical to the development of LDR; and technology development recommendations. Implied references to individual technical papers presented in panel meetings are indicated by the presenter's name in round brackets. Summaries of the papers can be found in the Appendix.

A. Controls and Pointing

1. Introduction and Review

In recognition of the importance of pointing and control technology to LDR, a panel has been convened at each of the three workshops to assess and plan the development of the technology base. The charter and structure of the panel were similar in all cases. The panel was constituted with members that possessed direct experience on the current state of the art programs relevant to LDR. The members were invited to make presentations on their work, assess the state of the technology, and evaluate the scope and depth of the proposed technology program. The following is a summary of the LDR technology assessment, and the proposed LDR technology program.

The Controls and Pointing panel for the third Asilomar conference had three major objectives: to determine the state of the art in relevant LDR pointing and control areas; to identify the specific needs and concerns for LDR technology in this area; and to recommend a development program to bring these technologies to readiness in support of an LDR mission.

The Asilomar II panel identified and prioritized seven key sensing and control technology areas as critical. These were:

- (1) dynamic control technology,
- (2) modeling and performance prediction,
- (3) wavefront and figure control,
- (4) control technology integration brassboard,
- (5) fine line of sight guidance and offset pointing,
- (6) chopping devices, and
- (7) flight-controls demonstration.

Of these, the first four were identified as having the highest immediate priority. The dynamic control technology is needed to

provide isolation of on-board dynamic excitation sources and was seen as the area where the Hubble Space Telescope has had some of its greatest problems. Significant advancements in control analysis and simulation tools will be needed to handle with high precision the close to 1000 degrees of freedom which the LDR has. Sensing of the wavefront and relating this to the telescope figure was identified as an issue in the correction of wavefront errors. The integration brassboard was called for to demonstrate proof-of-concept of the control hardware and algorithms in a ground-based demonstration.

The Controls and Pointing panel prepared a program plan in each of these seven technology areas. The program reflected the recommended priorities, covered five years, and culminated in the ground brassboard, and the flight-controls demonstration. Evaluation of the state of the art in each area was provided along with the growth projection provided by the proposed program.

2. Identification of Critical Technologies

At Asilomar III, the seven critical technology areas identified above were recast into six pointing and control technology needs so that they could be distinguished from the several functions of the spacecraft control system. These needs were then assessed for technology status as demonstrated by current flight and ground programs. The needs were measured on the standard technology readiness scale.¹

The most advanced systems demonstrating LDR technology are the Hubble Space Telescope (HST), which is a Shuttle-deployable telescope with excellent stability, maneuverability and a digital pointing control system, and the Keck Telescope, which is a segmented, ground-based 10 meter optical telescope. In addition, several research and development programs are preparing technology in pointing and control of large, flexible reflector systems. These include the Space Active Vibration Isolation (SAVI) program, the Joint Optics Structures Experiment (JOSE), and the Large Optics Demonstration Experiment (LODE). TABLE 3 compares the approach and expected contribution of these programs with the specific LDR technology needs.

¹NASA Technology Readiness Levels:

Level	Definition
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function/characteristic demonstration
5	Component/brassboard tested in relevant environment
6	Prototype/engineering model tested in relevant environment
7	Engineering model tested in space

TABLE 3. LDR Controls and Pointing State of the Art

PROGRAM	APPROACH/EXPECTED CONTRIBUTION	NEEDED LDR CONTROLS TECHNOLOGY
HST	f-separation: 0.6 Hz control vs. 18 Hz truss plus constrained system & user disturbances Expected to demonstrate pointing of single monolith to 0.01 arcsec on 18 Hz truss	Lightweight ($< 5 \text{ kg/m}^2$) Low power ($< 10 \text{ W/m}^2$) Cooperative pointing of 70-100 elements to 0.1 arcsec on flexible spacecraft
SAVI	Very high isolation of massive payloads in 100-2000 Hz with 12 actuator system using linear actuators and magnetic suspension	Integrated pointing, figure and vibration control
JOSE	Application and evaluation of modern control theory methods and active truss members. 1-500 Hz	Wavefront sensors suitable for LDR wavelength and surface quality
LODE	4.0 m in 4 deformable segmented panels on a rigid support - WF control at high B/W	Two-stage optics sensor/control concepts
KECK	0.05 μm segment control of 36 rigid monoliths on massive 5.4 Hz truss Segment control uses simple low performance approach: limited to 0.5 Hz by B/W stability Design approach: frequency separation, does not provide for vibration control or pointing interactions 108 Actuators: lead-screw plus 30:1 hydraulic mechanical advantage stage 168 capacitive edge sensors, and modified Hartmann tilt and piston sensor	Accurate prediction/modeling tools Controls, Structures and Optics integrated analysis and evaluation tools

The two systems specifically designed for astronomical observation, the HST and the Keck Telescope, deal with control issues of great relevance to LDR: the precision pointing of spacecraft, and the precision control of a segmented primary reflector. Issues not addressed by these systems include the effects of spacecraft flexure on pointing, and the control of vibration in the segmented primary support structure. To a degree these are addressed by the three ground-based experiments, but not as specifically required for LDR. The Precision Segmented Reflector program, an element of the Civil Space Technology Initiative, will begin this fiscal year to develop quasi-static figure control technology, and has augmentation proposals for dynamic control and wavefront control. None of these programs support, or presently plan to support, pointing control, alignment of the multiple optical elements, or two-stage optics.

TABLE 4 is a matrix of the functional requirements for LDR as a function of the various pointing and control technology disciplines. It gives the consensus of the panel on the technology needs and the current development status. A goal of readiness Level 5 (component or brassboard tested in a relevant environment) was assumed to be required before a Phase A study can be started. The rankings ranged from fully developed for pointing sensors (gyros) and rigid body pointing analysis and design, to Level 2 (conceptual design formulated) for system integration. Across all control system functions, the absence of mission studies that define disturbances was noted as a serious deficiency that will impede technology development progress overall. Insofar as it is possible to identify a general, across-the-board level of readiness, the panel felt that Level 3 (conceptual design tested analytically) and Level 4 (critical function demonstration) should be the near-term technology development goal.

TABLE 4 is intended to be read in both directions, that is, it is an assessment of the functional requirements within a specific technology discipline, and it is an assessment of a specific functional requirement across all technology disciplines. In terms of the functional requirements, figure control in the presence of vibration is at a low level of readiness. Although several research and development programs have been specifically aimed at dynamic control of large space structures, none have integrated vibration control with other functions (such as figure control) or demonstrated the technology experimentally. In terms of the technology disciplines, modeling and disturbance analysis are areas with a low level of readiness. Although the basic algorithms for modeling, simulation, and design may be in place, code systems which can handle the extremely large number of degrees of freedom in a segmented telescope are currently experiencing numerical difficulties. The disturbance modeling has not been delayed for lack of techniques,

TABLE 4. LDR Controls and Pointing Current Technology Status

	SENSORS	ACTUATORS	ALGORITHMS DESIGN	MODELING/ ANALYSIS	DISTURB DEFINIT	TEST / VERIFICATION INSTRUMENT & METHOD
SEGMENT TO SEGMENT FIGURE CONTROL	3	3 (PM) 2 (QM)	5 ^r 2 ^v	5 ^r 2 ^v	0	-
DEFORMABLE SEGMENT FIGURE CONTROL ^q	2.5	3	5	3	0	-
POINTING: Gyros Star tracker LOS transfer	7 5 2	6 3	7	7	0	-
SM and TM ALIGNMENT	3.5	6	7 ^r 2 ^v	7 ^r 2 ^v	0	0
WF CALIBRATION	3	-	3	2	0	large flat
DAMPING: Active Passive	3 -	3 -	3 -	2 2	0	μ -g acceleration x100 improvement
NODDING CHOPPING	- 6	- 4	2.5 4	2.5 4		0 0
INTEGRATED SYSTEM B/B and EVALUATION	-	-	2	2	-	facility system test bed

- Notes: 1. Superscripts: ^r = rigid body, ^v = vibration, ^q = quasi-static.
PM, SM, TM and QM refer to the primary, secondary, tertiary and quaternary mirrors.
2. Levels of Readiness are defined in footnote on page 11.
3. The recommendation is to carry the technology to Level 5.

but for lack of definition, and study of realistic, viable candidate spacecraft. Although this will improve as the system concepts mature, control and pointing technology development is presently hampered for lack of these crucial inputs.

3. Technology Development Recommendations

The technology development needs were prioritized as shown in TABLE 5. Two areas were given the highest overall priority: segment-to-segment figure control, and the integrated system breadboard. The areas of vibration control and wavefront calibration were also given a very high priority. With only two exceptions, all the areas considered were judged to have high risk if not developed. Control of deformable panels and the control impact of the spacecraft nodding observation mode were identified as two areas requiring further definition.

Essentially the same technology needs were identified as high priority by the Asilomar II panel. At that time, dynamic

TABLE 5. Prioritization of Technology Development Needs

NEEDED TECHNOLOGY	OVERALL GRADE	DIFFI-CULTY	IMPORT-ANCE	RISK IF NOT DONE
SEGMENT TO SEGMENT FIGURE CONTROL	H1	H	H	H
DEFORMABLE SEGMENT FIGURE CONTROL	L	M	?	?
POINTING	M	M	H	H
SECONDARY, TERTIARY QUATERNARY ALIGNMENT	M	M	H	H
WAVEFRONT CALIBRATION	H3	M-H	H	H
ACTIVE DAMPING PASSIVE DAMPING	H2	H M	H	H
NODDING	M	H	?	?
CHOPPING	M	M-L	H	H
INTEGRATED SYSTEM B/B and EVALUATION	H1	H	H	H

control technology (jitter control, structural dynamics, vibration isolation and active control) and the system breadboard demonstration were identified as the highest priority needs.

TABLE 6 contains a summary of the recommended technology development program. The limited resources available to the NASA technology community were recognized and only the essential program elements were included. Where possible, synergistic programs in place, or sponsored by other agencies, were utilized. For example, the technology of the PSR program is directly applicable to LDR, and is called out in TABLE 6 for augmentation only where absolutely necessary. The cornerstone of the development program is the integrated system demonstration where the level of development of control functions in addition to figure control, that is element alignment, pointing and deformable segment control, can be demonstrated. That program would be a six-year ground demonstration to finish concurrent with the initiation of the LDR Phase A studies.

TABLE 6. Recommended Technology Development Program

NEEDED TECHNOLOGY	ADDRESSED BY PSR	ADDITIONAL %	NEEDS M\$
SEGMENT TO SEGMENT FIGURE SENSING & CONTROL	50%	50%	3
DEFORMABLE SEGMENT FIGURE CONTROL	10%	90%	1
POINTING		100%	2
SECONDARY, TERTIARY, QUATERNARY ALIGNMENT		100%	1
WAVEFRONT CALIBRATION		100%	2
ACTIVE & PASSIVE DAMPING	10%	90%	4
NODDING CHOPPING		100%	1
INTEGRATED SYSTEM B/B and EVALUATION	10%	90%	10 ¹
TOTAL COST			24
COST/YEAR			4

Note: 1. Tool development (\$2M), B/B description and development (\$2M), fabrication (\$4M), testing and evaluation (\$2M).

B. Reflector Panels and Materials

1. Introduction and Review

The technology areas of panels and materials were combined with structures technology at Asilomar II. In this sub-section, we cover only the panels and materials recommendations of that group; the structures recommendations are reviewed in the following sub-section. The issues covered by the Reflector Panels and Materials panel included a review of Asilomar II results, the identification of critical technologies, and the specification of new functional requirements. Technical problems not addressed by the CSTI/PSR program were also discussed and evaluated.

The Asilomar II panel concluded that the development of lightweight, low-cost reflector panels that demonstrate high surface precision and thermal stability was the most critical technology. This recommendation was driven primarily by the unacceptable weight associated with using glass. The requirement for a light-bucket mode of operation was a secondary issue. Since glass panel technology could not meet the areal weight requirements, the recommendation of the Asilomar II panel was for the development of structural composite, glass, and metal panels. Since the light-bucket mode has now been removed (if it is a major cost driver), the recommendation of the Asilomar III panel is to focus only on lightweight structural composite panels because of their high potential payoff.

2. Identification of Critical Technologies

The specific technologies critical to the development of structural composite panels are discussed in this subsection. They include panel design, fabrication, coatings, surface refinishing, testing and analysis. Also included are the testing and analysis of alternate panel materials.

a) Panel Design

The design of structural composite panels entails the optimization of the baseline graphite/epoxy (Gr/Ep) material and layup, and possibly the development of new core concepts. The current baseline Gr/Ep materials, for example, can be optimized by enhancing the chemical bond between the carbon fibers and the epoxy matrix. Similarly, there are options for the current aluminum honeycomb panel core, such as composite honeycomb, composite tri-balance, and circularly symmetric. However, all of these options will have to be proven by the process of building and evaluating realistic size hardware. In this process, the manner in which the panel properties scale with increasing size will be determined and accounted for in the design and fabrication of full scale hardware.

The current baseline panel materials represent only one of a number of materials and their derivatives that might be suitable for the panel development program. The materials research program discussed below will identify or develop other materials for the baseline program.

b) Panel Fabrication

Fabrication addresses the processing, tooling, quality control, attachment, and mass production of panels. The large number of variables associated with composite material designs and their fabrication could result in a lack of consistency from panel to panel. Quality control techniques will have to be tailored for the baseline materials and processes. Since the fabrication of the baseline panel is based on experimental approaches, such as the laying up of facesheets by hand, consideration will have to be given to automating the process to accommodate the production of a large number of panels in a reasonable time frame. A significant contributor to the precision of the baseline Gr/Ep panels is the thermal stability of the ceramic tooling. Consequently, scaling factors associated with increasing tool size, will have to be developed to account for any differences in expansion rates and heat loading associated with panel curing.

The baseline panel fabrication involves the curing of single facesheets prior to the addition of the core. There are a large number of options for variations of this manufacturing process. Evaluation of promising variations might significantly enhance the panel development.

c) Panel Coatings and Surface Refinishing

The selection of coating materials could contribute to the ease with which panels can be polished, their reflectivity, and the amount of environmental protection afforded. Since these are all very important areas, panel coatings have great potential for improving the manufactured surface quality of lightweight composite panels. For post-fabrication surface refinishing to be effective, sufficient matrix material, or thick coatings, must be present to avoid fiber print through. Currently there are a number of options for polishing equipment and techniques, and they should be evaluated.

d) Testing

Extensive testing will be required for characterization of both the basic panel materials and the complete panels. At the present time, there is a lack of available test facilities to meet the specific needs of this program. Chambers for thermal vacuum, thermal cycling, and vacuum thermal cycling tests of up to 2-meter panels at 200 K with thermal gradients will be required.

e) Analysis

Analytical simulation at the system, subsystem, and micromechanics level will be required to accommodate panel development. System simulation defines the orbital environment of the panels for specific classes of applications; subsystem analysis characterizes the panel materials, thermal, structural and optical performance for specific applications and test conditions; and micromechanics analysis is needed to characterize viscoelastic material behavior, residual stresses, thermal fatigue, moisture dryout effects, and criteria for failure and verification testing. The state of the art for system and subsystem analysis is marginally adequate to support panel development. However, significantly more capability will have to be developed in the area of micromechanics analysis.

f) Alternate Materials

Alternate advanced polymer matrix composite materials have the potential to improve the performance of the baseline panels. Examples of such materials and processes would be low thermal expansion matrix resins, improved carbon fibers, and improved fiber/matrix bonding. Thermoplastic and thermoset polymers, for example, need to be synthesized and characterized for their physical and mechanical properties. Emphasis will be placed on developing low expansion resins which can be processed at low temperatures to minimize residual stress in cured composites. These advanced polymers would then be combined with specially processed carbon fiber to produce an advanced composite for physical and mechanical characterization. Promising candidate composites would be processed into sub-size panels to verify panel fabrication procedures. These panels would be tested to fully evaluate alternate material concepts and compared with baseline Gr/Ep systems. The most promising materials would then be selected for full-size panel fabrication.

Graphite glass (Gr/Gl) has been selected as an alternate material with great potential for panel development, but its materials properties must be better understood. Another material, sol-gel, is also recommended for development and evaluation because it is processed at low temperatures.

3. Technology Development Recommendations

Before the conclusions of the Panels and Materials panel are given, two other issues should be noted: possible changes in panel functional requirements, and panel work being done under the CSTI/PSR program.

Functional requirements from the technology areas of Systems, Controls and Science can impose significant constraints on the development of structural composite panels. For example, on-orbit assembly, launch loading, and outgassing requirements

could influence the basic design of the panels. Likewise, the optical properties of the panels needed to accommodate Controls and the high precision needed for the light bucket mode, if deemed necessary, affect the degree of technology development of the panels.

Materials issues currently not included in the PSR program should also be noted; these include the sunshade, the basic primary and secondary support structure, and the environmental effects on materials. The sunshade issues involve high performance polymer films, adhesives and coatings. Structural areas include composite tubes and adhesives while environmental concerns are related to atomic oxygen interaction with the materials and the effects of orbital contamination.

There was unanimous agreement within the panel regarding the general conclusions. Good progress has been made in developing an integrated panels and materials technology development plan. The key technical areas are being worked by PSR with support from the NASA materials base programs. There is a good probability of significant technology advancement at the current level of funding. However, system and operational constraints could turn out to be a major design driver and dilute to some degree, the specific technical tasks currently planned under PSR.

C. Structures

1. Introduction and Review

Structures recommendations at Asilomar II were made in three broad areas: structural concepts, structural system dynamic simulation, and flight experiments. The structural design goals established at Asilomar II were revisited, and the new goals are summarized in TABLE 7. The only significant changes are an increase in the thermal shield mass density (up from 1 kg/m²), and an increase in the system natural frequency (up from 1 Hz). The primary structural system drivers are performance, weight, cost, and operational reliability.

TABLE 7. Structural Design Goals for LDR

Primary Structure Mass Density	<	5 kg/m ²
Thermal Shield Mass Density	<	3 kg/m ²
System Natural Frequency	>	3 Hz
Structure Cost	<	\$10 K/kg
Passive Damping	>	3 %
Primary Structure Surface (rms)	≤	100 μm
Predictable Joint Performance		

The deployable and erectable structural concepts discussed at Asilomar II for the primary reflector backup structure are now being evaluated as part of the CSTI/PSR program. On-orbit panel attachment may prove to be a design driver, and is also being evaluated in the CSTI/PSR program. The impact of the sunshield remains to be determined. The requirements for structural system dynamic simulation include evaluation of the micron-level static and dynamic characteristics, wave motion propagation, structural damping, and the development of analytical methods for their prediction. Although our understanding of these issues has improved, very little technical effort has been performed in the country to quantify the issues. These remain unresolved, as do issues associated with validation by ground test, which is expected to be a major technical challenge. The requirement for a flight experiment before LDR has now been relaxed under the assumption that other missions would help resolve key issues.

2. Identification of Critical Technologies

Three technology areas have been identified as important areas of research for LDR; they include structural concepts, structural system dynamics, and ground validation test methods. Their requirements are unique to large multisegment structures that require micron level figure definition.

a) Structural Concepts

Structural concepts needing further development include the sunshade, panel attachment, and adaptive structures.

i) Sunshade

The current sunshade concept consists of accordion folded multilayered insulation (MLI) blankets; these are deployed through a number of ASTRO-type mast structures uniformly distributed around the perimeter of the primary structure. The potentially large mass and relatively low modal frequencies associated with the sunshield may significantly affect the technology requirements for LDR. An effort to better define the sunshade characteristics is recommended as being necessary to help assess the potential problems and to assure the proper direction for technology development in structures and controls.

ii) Panel Attachment

Panel attachment by astronauts and/or robotic means is seen as another area requiring better definition. Key questions include how to attach the panels to the structure from the front without being able to see the attachment points, how to protect the mirror surfaces during assembly/disassembly, and how to remove a panel (if necessary). Currently, no feasible structural concepts exist to achieve the assembly and disassembly of the panels. An effort in panel attachment and removal is recommended so that a feasible approach can be identified which meets the requirements of LDR.

iii) Adaptive Structures

A structural concept referred to as adaptive structures could have a significant impact in helping to meet LDR structural requirements. It involves the use of active structural elements which, by either local or remote control, respond to adjust relevant structural parameters. With the ability to control micron-level displacements in the frequency range from 0-200 Hz, appropriately placed active elements can be used to: (1) provide increased structural damping, (2) adjust the initial static position of the structure if required, (3) maintain relative positions during temperature changes, and (4) provide a means to preload joints and provide structural isolation. A significant advantage of adaptive structures is that they may be utilized with a ground test program to validate the on-orbit performance of a structural system.

b) Structural System Dynamics

i) Micron Level Response

At the present time it is not possible to analytically predict either the static or the dynamic micron-level response of large structures constructed of struts and joints. This is not limited to the prediction of modal eigenparameters, but also includes the quasi-static response to thermal changes, and the prediction of the initial static position in space. This information is important to establish the static and dynamic range requirements for sensors and actuators. Existing test data for deployable trusses indicate that joint nonlinearity (or "slop") prevents the identification of modal eigenparameters at about the 0.1-g level, and that existing measurement capabilities are limited at about the 0.001-g level. Therefore, at the anticipated response levels of interest to LDR (a peak displacement of $1\text{ }\mu\text{m}$ at 1 Hz corresponds to $4\cdot 10^{-6}\text{-g}$), a high probability exists that a structure cannot be modeled in terms of its eigenparameters, and some other means must be found to characterize it. More accurate test measurement methods must be developed to obtain the data necessary to help in the formulation of the analytical model, which may possibly be statistical in nature.

ii) Wave Motion

During testing of the Space Station structure, the transfer of energy through the structure (when it was subjected to an external force) was visually observed; the path of energy transfer depended on the location and direction of the applied force. Although this wave motion could in principle be described as a superposition of eigenvectors, the large number of eigenvectors, and their associated uncertainties, quickly deteriorates the fidelity of the representation. The impact of this wave motion on LDR must be evaluated.

A semi-empirical approach to develop an energy transfer model is recommended. When a reasonable model is developed, methods to attenuate the wave energy by a damping mechanism (such as an active element) near the source of the energy input, or in the path of the energy transfer, should be employed.

c) Ground Validation Tests

A ground test capability is needed to measure micron-level structural deformations be they static, quasi-static, or dynamic. In addition, ground test approaches must be able to accurately extrapolate results of thermal vacuum tests from subsystems to entire structures because a thermal vacuum chamber capable of testing an entire structure is not available. In addition, the gravitational loading on an entire structure may result in unrealistic preloads, and thus in unrealistic thermal conductance characteristics. Without the development of the ground validation test techniques for critical performance

parameters, the LDR program office may never commit to a flight project. Adaptive structures concepts may provide additional ground test/analysis options.

Preliminary analysis of a LDR deployable backup structure has indicated that the structural stiffness may be sufficiently high to allow a determination of its on-orbit static deformation by ground test. The quasi-static and dynamic characteristics will be much more difficult to quantify, and ground test limitations are anticipated. When determined, either new ground test approaches must be developed, or the structural concepts must be modified to fit within the ground test limitations. The committee recommended this approach be used for LDR; a flight test is not absolutely required.

3. Technology Development Recommendations

Structural technology development recommendations follow directly from the critical technologies identified in the previous subsection.

Although several erectable or deployable LDR backup structure concepts exist, which appear to meet the current program objectives, they do not take account of the LDR sunshade. Because of its potentially large torques and low modal frequencies, the sunshade may be an important design driver. A representative LDR structure with a sunshade must therefore be evaluated. A question exists as to whether a meaningful PSR test model, and program to address the LDR technologies, can be developed.

Other structural concepts needing definition include methods for attaching panels and employing adaptive structures. The latter may in fact help define a meaningful ground test program.

The extrapolation of limited experimental evidence indicates potential difficulty in predicting on-orbit wave motion and micron-level structural responses. Better test and analytical methods will have to be developed to understand these structural performance characteristics, and establish their impact on the LDR mission. If the current structural concepts do not meet the necessary performance characteristics, alternative concepts must be developed. Efforts to develop ground test/analysis methods to validate the performance of the structural system is required.

A flight test is not considered mandatory for LDR but would be highly desirable. This statement rests on the assumption that other missions would be flown prior to LDR that would help to resolve the important structures technical issues.

D. Receivers and Cryogenics

1. Introduction and Review

At the Asilomar II workshop, the technology areas of receivers and cryogenics were considered separately; receiver technology was studied by the Science Instruments panel, and cryogenic technology was part of the Thermal and Power Technology panel. Since stored cryogen mass and lifetime are such important considerations for LDR, it seemed essential that cryogenicists be able to interact directly with receiver developers. Hopefully in this way, realistic numbers might be found for anticipated operating temperatures and heat loads.

As the result of the discussions of the Receivers and Cryogenics panel, it was evident that a broad and diverse, although generally immature, technology base exists in this area. The following summary represents a general consensus of the panel. It was evident that progress has been made in all technology disciplines since the previous Asilomar workshop; in some cases, the progress was spectacular. However, as has been stated before, without a long-term, focussed development program, the technology base will fall well short of LDR instrument requirements.

2. Identification of Critical Technologies

The technology areas critical for LDR instrumentation include submillimeter heterodyne receivers, direct infrared detectors and detector arrays, and cryogenics. This subsection evaluates their status and requirements.

a) Submm Heterodyne Receivers

Significant progress is being made in this field, which until recently was largely unexplored. Systems are now working in the laboratory and in ground-based and airborne observing environments. Expertise is developing in a number of institutions in the US and Europe, as was evidenced by the lively debate which occurred on various issues. One needs to keep in mind, however, that in absolute terms this area is still quite new, and well below the level needed for LDR instrument development.

i) Mixers

A number of groups are now using GaAs Schottky diode mixers very successfully in operational systems. For example, the Kuiper Airborne Observatory (KAO) has used this technology at wavelengths longward of 150 μm . Relative to other mixer technologies, GaAs Schottky diodes have the advantages of wide frequency response, only modest (~ 60 K) cooling requirements, and availability. In the 100 GHz region, these systems

have achieved (double sideband) noise temperatures ~ 20 times the quantum limit; at about 1 THz, this factor is about 150 times the quantum limit (Betz). They do, and will, require local oscillator (LO) power on the order of mW's. At present, there is only one useful source of these GaAs diodes (U. Virginia).

There is a very high level of interest now in superconductor-insulator-superconductor (SIS) mixer development, with about 10 groups in the US and Europe pushing the state of the art. At this point, Pb-based SIS junctions (≤ 4 K) have been operated up to 1.1 THz in the laboratory (Frerking). For frequencies < 200 GHz, a system noise about 10 times the quantum limit (double sideband) has been achieved. A promising recent development involves the use of Nb-based alloys for SIS mixers. NbN mixers should be more rugged, operate at somewhat higher temperatures, and ultimately achieve higher frequencies (possibly 3 THz). SIS mixers require only low levels of LO power (order of μ W's) and have wide IF bandwidths.

Encouraging progress has been made in the use of SIS mixers. At lower frequencies, inductive elements have been added across the junctions to effectively tune out capacitance. A range of creative antenna technologies has emerged as well; this work also supports the move toward arrays of mixers.

A measure of the progress in this area is the opinion that the heterodyne array instrument conceived of in the 1984 LDR Phillips-Watson report, which was then considered to rest on technologies which were "only a hope," was felt to be quite feasible now. It was felt that with sustained support, the necessary technologies for a linear array could be demonstrated in less than five years, with efforts focussed on achieving smaller device dimensions.

Photoconductive mixers were briefly discussed, but it was felt that these devices were not competitive with Schottky and SIS mixers because they have slower response times and require tunable local oscillators for spectroscopy.

ii) Local Oscillators

CO₂-pumped far-infrared lasers ($\sim 1-3$ THz) have been successfully implemented in ground-based and airborne systems (Betz). They are adequately compact, and provide the milliwatts of drive power needed by Schottky diode mixers. Although the LO power is available only at specific frequencies determined by the transitions of the lasing gases, many of the most interesting astrophysical lines are accessible with CO₂-pumped far-IR lasers. An effort is now starting to make these LO's space qualified, and to develop means of extending the CO₂ pump laser lifetime.

Significant improvements have been made in the area of resonant tunneling oscillators (quantum well oscillators) (Sollner). Through the use of layered structures in the GaAlAs system, solid-state submm "electronic Fabry-Perot" oscillators have been demonstrated. Early this year, output power of about 0.2 μ W was demonstrated at 200 GHz. (Thirteen months earlier, the upper-frequency limit was 20 GHz.) The series resistance and thickness of the device have been identified as limits to the performance; with continued improvements in these parameters, operation up to \sim 1 THz is projected.

As a result of this work, a dramatic advance has also been seen in multiplier technology. It has been shown that odd harmonics can be generated when a sine wave is swept over the I-V characteristic of the resonant tunneling oscillators. With this new technique both third-harmonic (67 converted to 200 GHz, with 250 μ W output) and fifth-harmonic (42 GHz converted to 210 GHz, with 10 μ W output) multiplication has been demonstrated. Other new results establish quantum well multipliers as already being competitive with conventional GaAs-diode triplers. Higher-harmonic generation is also possible with multiple quantum well structures.

Work on backward wave oscillators (BWO's) is underway in Europe and the U.S. The U.S. effort involves a planar, photolithographically-produced structure which should have better efficiency than the machined structure pursued by ESA, although this work has not yet achieved a clear demonstration of useful output power. There was concern about whether BWO technology could be space qualified, although the Europeans have achieved 950 GHz using carcinotrons, and are baselining these tubes for space applications.

iii) Back-end Electronics

Acousto-optical spectrometers (AOS's) are in common use on ground-based systems. In Europe, they are favored for space applications. It is felt that the AOS can be space-qualified and made more efficient through the use of polarizing Bragg cells and laser diodes. The digital autocorrelator approach has the advantages of being smaller and presumably more reliable, but power dissipation is higher. Digital systems now operate at \sim 0.1 W/channel; it was projected that through optimal design and application of VLSI technology, the power consumption could be reduced by an order of magnitude (Wilson).

b) Direct Infrared Detectors

In contrast to the relatively uncharted field of submm heterodyne receiver technology, the ongoing development program focussed on SIRTf needs is providing a significant technological heritage for LDR instruments (McCreight). This work is applicable directly for wavelengths $>30 \mu$ m, and also indirectly,

since low-noise readouts and materials advances for shorter wavelengths provide supporting experience. SIRTf technology will not be optimum for LDR, however, since the comparatively high LDR background and the larger desired long-wavelength detector array formats will require development, characterization, and optimization.

i) Detector Materials

A wide range of extrinsic silicon and germanium detector materials is being evaluated. Both conventional bulk photoconductive and impurity band conduction (IBC) (e.g., blocked impurity band (BIB)) detectors are under investigation. Ge:Ga IBC detectors have recently demonstrated long-wavelength response ($\sim 200 \mu\text{m}$) and promising quantum efficiency in a non-optimum device. This development has the potential of replacing the conventional (stressed and unstressed) bulk Ge:Ga arrays on SIRTf (and LDR). Studies of Ge:Ga geometrical effects have shown the advantages of using a beveled back face to increase optical absorption.

ii) Modular IR Array Technology

The very low inherent noise of Si JFETs has been exploited in recent advances in integrating readouts. Both single-channel and 16-channel versions have been produced, with read noise on the order of 10 electrons (Young). Vibration tests have indicated that this technology is space-qualifiable, and it may see application in the HST second-generation instruments, SIRTf, and ISO. These readouts are in principle compatible with any IR detector material, and array sizes up to 32×32 , or 64×64 , are presently planned.

iii) Hybrid Arrays

Tremendous interest has been shown in the application of integrated IR array technology ($< 30 \mu\text{m}$) in astronomy. Arrays of intrinsic and extrinsic materials, in photovoltaic, bulk photoconductive, and IBC forms, are being evaluated. Formats of 64×64 are now common, with larger arrays being actively developed. In general, integrated arrays have shown responsivities comparable to those of good discrete detectors, read noises at and below 100 electrons, dark currents in the range 1-100 electrons/second, and modest ($< 1 \text{ mW}$) power dissipation. The body of knowledge and experience in the photometric use of these arrays in astronomical observations is growing. This provides an important adjunct to SIRTf technology developments for LDR. While the overall capabilities of arrays have been demonstrated, finer points such as temporal response, response to energetic particles, and imaging properties remain to be fully proven. These may be crucial for space applications.

iv) Bolometer Arrays

Small arrays of bolometers are being used in ground-based and airborne systems. For space applications in the 200-1000 μm range, they are presently the technology of choice. A small array of bolometers is baselined for the SIRTf photometer instrument; for this project, the initial thrust has been in the design and definition of a workable adiabatic demagnetization refrigerator to achieve 0.1 K. Discrete bolometers at this temperature have demonstrated NEP's of approximately 10^{-16} W/Hz (Meyer). The challenges associated with application on LDR include building arrays of $\sim 10 \times 10$ elements, and optimizing these systems to the background loads of LDR.

c) Cryogenics

The cryogenics specialists on the panel had great difficulty in matching the state of the art to LDR requirements, since the LDR heat loads, minimum temperature requirements, instrument configurations, and operational timelines are poorly defined. A strong recommendation was made to improve the definition of the LDR system configuration, and to establish an active dialogue between the cryogenicists, the users, and systems engineers. Despite the level of uncertainty, the following general description emerged from the discussions of the panel.

Space hardware experience with stored cryogens (i.e., superfluid He) has been gained through IRAS, the Spacelab Infrared Telescope, and the upcoming COBE mission. For a 1 W-yr load to the dewar, 10 m^3 of He II are needed, or about 1400 kg of liquid. (Tankage, shielding, and supports could increase the mass by as much as a factor of ten (Mason).) Assuming a negligible instrument load, it has been estimated that stored He II technology could provide up to five years of cooling in space. The control of the liquid is the primary issue in long-life containment, and the achievement of a long-lived LDR would rely upon reliable resupply techniques. The Superfluid Helium On-Orbit Transfer (SHOOT) experiment will address this issue; it is planned for flight in advance of SIRTf, which baselines this approach.

A range of active coolers has been supported by NASA and DOD. Some progress in this field has been evident, for example, the ~ 2 year unattended lifetime demonstrated with Vuilleumier and Stirling coolers. There is also encouragement about progress with various Brayton-cycle machines such as the Turbo-Brayton and Rotary-Reciprocating Refrigerator coolers. Stirling technology has achieved a minimum temperature of 40 K. These coolers require about 3 kW of input power, and for space, a substantial radiator to reject heat. Concerns about vibration and lifetime might require that multiple, switchable active coolers be used on LDR. Sorption coolers are becoming increasingly effective for cooling in the 20-80 K range. These units operate with thermal efficiencies lower than those of the Vuilleumier and Stirling

coolers, but they are free of vibration, and could conceivably utilize waste heat. No lifetime demonstrations have been carried out for this technology. Joule-Thomson expansion concepts may be applicable, particularly in cascaded configurations. However, this approach, while simple, suffers from low efficiency and the possibility of clogging. There is a renewal of interest in magnetic cooling concepts for the 10-15 K range. Progress here seems to be materials-limited. There is also a 2 K magnetic cooler about to reach the commercial market.

In the sub-Kelvin cooler area, the adiabatic demagnetization refrigerator, under development for SIRTf, is capable of reaching <0.1 K with an inherently gravity-independent system, but with some concerns over the effects of magnetic quench (Kittel). For 0.2 to 0.3 K, ^3He systems are reasonably advanced. A component-level laboratory demonstration has shown successful operation in an inverted (minus 1-g) geometry, and a ^3He cooler is planned to fly on an upcoming sounding rocket experiment. There is also substantial laboratory experience with $^3\text{He}/^4\text{He}$ dilution refrigeration. Efforts are now beginning to adapt this technique to the microgravity environment of space.

The panel discussed the feasibility of changing out LDR instruments. Studies for SIRTf have generally found this to be a very challenging proposition, although it is considered feasible. The desirability of automating these operations, both in manipulating instruments and in retrieving the telescope system from higher orbits, would involve significant additional complexity. Another approach would be to configure the LDR focal plane with about four instruments, with an integral cooler, and to replace this with another module every few years. Another bold notion emerged in discussion: launch the LDR warm, and cool it on-orbit (Nast). While sacrificing the ability to check-out the operability of instruments on the ground before launch, this approach would greatly reduce the system mass by eliminating the need for the vacuum shell.

The panel revisited the heat load estimates on the strawman instruments from the Phillips-Watson report developed at Asilomar II (cf., [4], p. 88). It was concluded that substantial reductions were possible if instrument configurations were optimized to minimize loads on the cryogenic system. This preliminary revision was by necessity done quickly, and much more detailed work is needed. It does, however, reflect technological progress in the past 2-3 years, and illustrates the sizeable improvements possible in this area. The key improvement was achieved at 2.5 K, where the load was reduced from ~ 1 W to $\sim 1/4$ W, making a stored-cryogen system feasible. The revised estimates of instrument power dissipation (expected to dominate over aperture and parasitic loads) are tabulated in TABLE 8. The columns headed "old" refer to Asilomar II estimates of the receiver operating temperatures and power dissipation; the "new" values represent the current estimates.

3. Technology Development Recommendations

As was stated above, the panel concluded that significant progress has been made since the last Asilomar meeting as a result of the LDR technology development plan. There was a general endorsement of the goals and directions of that plan. However, the following recommendations were developed by the panel to help focus, and in some cases redirect, the key development areas. They are listed roughly in order of priority.

a) General

- o With the critical dependence of the mission on a reliable and workable instrument cooling scheme, support should be given to the development of techniques or configurations which would reduce instrument power levels and heat loads, and/or to increase the temperatures at which instruments reject heat to the cooling system.

- o Continuing development and experience has indicated that some of the instrument types (and their frequency limits) conceived at the time of Asilomar II should be reconsidered. As an example, there now appears to be no advantage in including a photoconductive heterodyne receiver (cf., [2], Fig. 3-1, p. 32); its role could be assumed by extended-range SIS and Schottky diode receivers. The photoconductive receiver would offer advantages at the shorter wavelengths if bandwidths were increased or tunable LOs available.

- o The panel recommends that observational testing of advanced receivers/arrays should be treated as an integral part of the LDR technology program. In the case of heterodyne receivers, platforms such as the KAO and SOFIA provide an excellent proving ground for development and optimization.

- o In the continuing definition of the LDR focal plane, the issue of "light pollution" must be addressed. The panel was concerned about the presence of local oscillator sources, and warm instrument components, in close proximity to instruments which cannot tolerate stray radiation.

- o It appeared that with the significant background levels of LDR, the conceived bolometer array instrument would not require cooling below 0.2-0.3 Kelvin.

TABLE 8. Old and New Instrument Power Dissipation Estimates

Instrument	Operating T		Dissipation	
	Old (K)	New (K)	Old (mW)	New (mW)
1. High-Resolution Spectrometer 400-3000 μm	20 4	40 8	300 10	100 1
2. High-Resolution Spectrometer 200-500 μm	20	20	300	20
3. Photoconductor Spectrometer 35-200 μm	20 4	20 2.5	- 100	10 5
4. Fabry-Perot Interferometer 35-200 μm	4 2	4 2.5	- 40-80	5 100
5. Grating Spectrometer 35-200 μm	20 4 2	- 4 2.5	100 - 6-40	- 1 50
6. Heterodyne Array	20 4	40 8	1000 350	1000 10
7. Far-Infrared Camera 35-200 μm	2	2.5	30	60
8. Submm Camera 100-1000 μm	4 0.1-0.3	2.5 0.3	10 0.01	10 1

Instrument Operating Temperatures	Total Dissipation	
	Old	New
0.3 K	0.1 mW	0.1-1 mW
2.5 K	980 mW	225 mW
8 K	360 mW	11 mW
20 K	2610 mW	(?) mW
40 K	- mW	1110 mW

b) Submm Heterodyne Receivers

- o With the promising initial steps in NbN SIS mixer development, support in this area should definitely be continued. At present, only one institution (JPL) is involved in this work; it is desirable that another source (e.g., U. Illinois) be developed.
- o Means must be found to correct the intermittent support given to the U. Virginia group which produces GaAs Schottky diode mixers; continuous and direct funding at a modest level needs to be arranged. An increased level of technical dialogue between these investigators and the user community would also be helpful.
- o The recent progress in quantum well oscillators and multipliers has been dramatic. The panel recommends that funding in this area to the MIT/Lincoln Laboratory be increased.
- o Funding for the planar backward-wave oscillators should be phased out, due to the lack of significant progress to date. (Note: Promising BWO data became available after the Asilomar III workshop. This recommendation should thus be reevaluated.)
- o CSTI funding has recently been obtained for development of an LDR-oriented FIR/CO₂ laser (GSFC). Support for this project should be sustained for a period of time to assess the feasibility of a space-qualifiable system.
- o The panel concluded that support for Gunn-LO/multiplier development is at present adequately funded from non-LDR sources.
- o The development of VLSI chips for a low-power, high-bandwidth digital autocorrelator was supported.
- o It was suggested that additional KAO/SOFIA flights be funded as a means of developing and gaining experience with prototype LDR instruments.

c) Direct Infrared Detectors

- o The ongoing SIRTf developments are providing an important foundation for LDR detectors, and support for this work should be maintained. The panel supported efforts to adapt SIRTf designs for LDR needs (e.g., minimizing thermal conductance of leads, optimizing circuits).
- o The Ge:Ga IBC/BIB detector development(s) should be continued. Exploratory projects now underway for SIRTf should incorporate or anticipate LDR needs, where possible.
- o In view of the cryogenic challenges presented by LDR, it was recommended that improved low-temperature, low-dissipation FET's and multiplexers, with characteristics such as charge-handling capacity tailored for LDR, be developed.

- o Support should be given to the development of LDR-scale bolometer arrays. Optimization of the size and geometry of the bolometer elements, and their time constant, is needed.

- o LDR instruments will require a range of optical elements (Fabry-Perot filters, mirrors, gratings) with large physical dimensions. Development of large prototype elements is recommended.

d) Cryogenics

- o As was indicated above, the panel emphatically recommended that the definition of instrument heat loads, temperatures, and duty cycles be improved. Improved means of managing the thermal loads from the LDR aperture should be identified. A formal dialogue between the cryogenic experts, the sensor and instrument developers, and system engineers should be established, and improved system studies should be undertaken.

- o The panel identified means of reducing the cold-end heat loads to well below 1 W. Given this, a stored-LHe cooling system should be considered to be a workable option. On-orbit resupply then becomes a key element in achieving a long-life LDR. Ongoing developments on resupply for SIRTf should be closely monitored.

- o The panel recommended continuing the development of active cooler technology for the 2.5-10 Kelvin range, as another important option. Support for sorption coolers should be sustained. Magnetic-cycle coolers appeared attractive for LDR; selected developments in this area should be pursued. The panel noted that present funding levels for active coolers are inadequate to seriously address LDR cooling needs.

- o Resupply needs for LDR should be incorporated in the design of the He II Tanker, by August 1988.

- o The definition of instrument changeout concepts must be improved. Changeout of a module including a number of instruments and an integral, "throw away" cooling system should be studied. The prime LDR instrument configuration must be developed in close coordination with the cooling concept.

- o For cooling of the bolometer arrays, if a minimum temperature of 0.3 K is acceptable, the existing ³He cooler technology is adequate. If 0.1 K is required, the SIRTf-baseline adiabatic demagnetization refrigerator should be closely monitored; in addition, exploratory dilution refrigerator concepts should receive continued support.

E. Optics and Systems

1. Introduction and Review

The technical disciplines of Optics and Systems were combined into a single panel for the Asilomar III workshop. In part, this was a response to the fact that LDR will operate in the submillimeter wavelength spectral region, where neither infrared nor radio techniques alone are sufficient for dealing with the optical design. Because this region cannot be adequately observed from earth, the incentive has not existed, as for other spectral windows, to develop the needed technology. The effect of diffraction in a segmented aperture, and the impact of background radiation from a passively cooled telescope, become very important system drivers which are unique to LDR. It is therefore essential that a very close interaction occur between all LDR technology areas, particularly optics and systems.

The Asilomar II Optics panel recommended work in the five general areas summarized below:

- (1) optical design and modeling
 - quasi-optics analysis and optimization
 - image quality evaluation and optimization
 - chopping and thermal background management
 - standing wave behavior
- (2) technology demonstration
- (3) precursor science
- (4) wavefront sensing
- (5) optical contamination

With the exception of optical contamination -- which awaits requirements for panel emissivity and reflectivity -- some progress has been made in each of these areas. At the two panel sessions during this meeting, the primary issues centered on the baseline design performance, chopping as a system driver, science instrument definition status, and optical testing for panel figure and alignment.

At Asilomar II, a JPL report introduced the concept of a two-stage, or four mirror, optical configuration for the LDR [3]. Although this design had several important advantages, subsequent studies have helped to reveal some of its limitations. A thermal background stability of about 1 part in 10^9 is required for sub-millimeter continuum measurements. This is achieved by moving the telescope beam back and forth on the sky ("chopping") with everything else held constant. In principle, the unwanted thermal background radiation is subtracted out and only the source radiation is measured. In the two-stage optical design, chopping can be accomplished by tilting the quaternary mirror. This is advantageous because the mirror is flat, which minimizes

image degradation, and it is small, which minimizes vibration (compared to chopping a more massive secondary mirror). Recent analysis, however, indicates that the hole in the quaternary mirror can cause an unbalanced sidelobe energy loss during chopping; this reduces the effective beam stability to about 1 part in 10^4 (Wright). Assumptions in this analysis need to be reviewed. In addition, there are potential problems arising from thermal variations, structural motions, and pointing control system errors. Discussions at the panel meetings strongly suggest that there are several key issues in regard to beam chopping that must be resolved before further progress can be made on updating the baseline design concept. Two options need to be considered for the updated baseline design: (1) a two-mirror Cassegrain with a chopping secondary, and (2) a modification of the four-mirror two-stage case. Both have potential problems, and understanding the trade-offs is essential.

At Asilomar II, it was recommended that a software analysis package be created to accurately model the optical system in terms of the Gaussian beam and white light performance. Between the two Asilomar meetings, a diffraction model of the LDR baseline system was used to determine qualitatively the side-lobe heights in a segmented aperture (Van Zyl), but much more work is needed to quantitatively evaluate the LDR quasi-optical design. This analysis has shown that the large secondary mirror of the baseline design causes unacceptable degradation of the diffraction pattern.

Wavefront sensing was recognized to be an important aspect of LDR for panel alignment. Work has been done on the application of a Shack interferometer to an alignment scheme for the Keck telescope (Vaughan), and on a technique for imbedding a weak diffraction grating in panels that could be used for real time sensing of panel alignment (Stier).

At Asilomar II, technology demonstration was called for in the area of reflector panels (both glass and composite), aspheric surface fabrication, and the development of two meter composite panels. This work is now funded under the CSTI/PSR program at JPL and LaRC, or planned augmentations to this program. There was substantial discussion as to the relationship of PSR to LDR technology issues. The PSR program is a natural vehicle for systems-level testing -- in hardware -- that could greatly benefit future LDR technology development and evaluation.

Progress was also seen in the area of optical metrology and the testing of panel performance over the needed temperature range. Several Dornier 50 cm panels have been measured in air at the Steward Observatory (Hoffmann) using a modified commercial interferometer provided by the JPL Optical Sciences and Applications Section. The total figure change observed was within the acceptable range for LDR applications. The next major hurdle will be to scale the testing capabilities to the full two-meter

panels. To improve the surface quality of the panels, thick SiO coatings have been applied to a Dornier panel, which was then polished using conventional techniques (Woida). This approach works, and has no affect on the panel figure change with temperature. Conventional polishing, however, would seem to be too expensive for the large number of panels needed for LDR. Overall, the work on panel development has been well coordinated and appears likely to achieve the goals required for the LDR reflector.

2. Identification of Critical Technologies

The basis for current LDR studies is given in a JPL report [3], and is also reflected in the Lockheed reference concept presented at this meeting [6]. Adjustments were made to accommodate refinements in the science requirements for the light bucket mode, and the shortest wavelength for diffraction limited performance. Consideration must also be given to the potential diffraction problems noted above, since this can impact the background rejection and faint source detection capabilities of the current two-stage optical design.

a) New Functional Requirements

New functional requirements were felt to be needed in a number of areas: thermal background suppression, panel surface properties, a system error budget, optical requirements on the control and pointing systems, and wavefront sensors.

i) Panel Surface Properties

Uniformity of the panel reflectivity and emissivity, as well as the possible need to have specular panels in the visible, requires the establishment of a specification for the coating/substrate system. Panel durability and aging must also be better understood. During the past two years, coatings have been developed over a Gr/Ep facesheet to enable the surface to have a high reflectivity for a period of several days -- long enough for a measurement of the optical wavefront. However, long-term stability of the LDR panels, and the spatial variation of emissivity, contamination, and staining have not been addressed. The use of glassy compounds for mirror surfacing must also be investigated.

ii) Science Instrument/LDR Modeling

As yet, no firm functional requirements for the desired LDR sensitivity limits at different wavelengths exist. These are clearly driven by science needs, and must be defined.

iii) System Error Tree

A complete system error budget is badly needed. To this end, subsystem functional requirements for the tilt, piston, and de-center of each of the panels, and for the ensemble of panels, are needed. These will be driven by the science requirements and could be evaluated by studying the time-dependent modulation transfer function (MTF). An optical interferometry experiment is also required to measure the opto-mechanical properties (e.g., CTE, hysteresis, joint non-linearities) of candidate opto-mechanical structural configurations. Ultimately, this should produce a comprehensive error tree for a given system performance/science requirement trade.

b) Optical System Design for LDR

Members of the Optics and Systems panel feel that an on-going optical system design activity should be initiated to provide a point design for LDR; this activity should take into account technology developments during the past three years, and should include a strawman payload of instruments. The panel recommends that the optical design activity continue during the LDR development program to provide ongoing support. A specific design activity would be the tolerancing of one- and two-stage segmented LDR mirrors in terms of the focal plane point spread function (PSF). This task should be performed for both an on-axis system and an off-axis system.

c) Modeling and Verification

A thermal model for the one- and two-stage LDR optical trains must be developed. These models should be of such precision that temperature and emissivity variations across mirrors, or between mirrors, can be evaluated in terms of noise power at the detector of a modeled science instrument.

Additional diffraction analysis of the segmented one- and two-stage LDR options must also be performed. This will require the merging of radio and optical analysis techniques into new software which can be used to compare model predictions with laboratory measurements.

Questions were raised about the reliability of the current panel measurement system, because it lacks adequate environmental control during testing. The recommendation was made that panels developed for space-based applications be tested in a thermal vacuum.

d) Adaptive Optics/Interferometric Metrology

Adaptive optics and interferometric metrology were identified as important technology areas. Time-dependent

deformations in large telescopes reduce image acuity, and will certainly affect LDR. Solutions to this potential problem will require the use of deformable mirror technology and optical image reconstruction techniques.

3. Technology Development Recommendations

In order to formulate a set of final recommendations the following questions were submitted to the panel for consideration:

- o Is the baseline design adequate? If not, what should the updated baseline be?
- o Are the control concepts able to deal with panel control, chopping, and pointing?
- o Is a strawman science payload required in order to do an end-to-end system analysis?
- o Is the current development work relevant?

As indicated in the prior discussion, there are concerns about the baseline design and the control concepts for meeting the background stability requirements. In a broader sense, it seems that many of the key issues, such as the impact of chopping on the system, will need a better definition of the science instruments in order to make the appropriate design trades. Current development efforts seem well directed in the structures and materials technology areas, as indicated by the excellent progress made in panel development. However, the Optics and Systems panel was clearly concerned about the integration of point technology developments into the LDR systems concept. Based on these concerns, the following recommendations were agreed on:

- o Establish multi-disciplinary teams to study the chopping problem and to select a set of science instruments that can be used for systems definition and performance analysis.
- o Develop alignment concepts and a systems error budget for the baseline design to establish the functional requirements for the PSR program.
- o Model the optical system from end-to-end in order to answer critical issues affecting LDR science objectives and their implementation.
- o Develop an updated baseline optical configuration for LDR, and identify the associated trade-offs, especially in the area of background stability. The numerical requirement for the level of background stability must be provided by the Science panel.

V. SCIENCE PANEL REPORT

A. Introduction

The Science Panel at the Asilomar III workshop consisted entirely of members of the LDR Science Coordination Group (SCG). The SCG serves the LDR project in several capacities: by providing the science rationale, by establishing system requirements, and by serving as an advocacy group. At Asilomar III individual science panel members were in attendance at each of the technical panel meetings, where they served several roles. One was an interactive role: to relate the LDR design to its science goals and to help define the key areas to be addressed. Sometimes the issues were unclear, leading to a second role: to determine the need for in-depth studies to refine the LDR design. Several of these studies involve system-level modeling to determine the effects at the focal plane of telescope vibration, thermal fluctuations, and the overall optics design. A third, and important role for the science panel, was to learn more about the LDR mission design, and to set up priorities for a science program leading to LDR itself. In some cases, LDR technologies are driven by astronomy goals which could be made more specific with preliminary results in hand. These results are usually observational, but could also be theoretical.

The main product of the science panel is therefore a preliminary plan to sharpen the science input to LDR and to keep the science needs closely related to the NASA-supported technology program. A detailed plan will be formulated in subsequent meetings of the SCG. The tentative plan includes special studies, workshops, and experimental and theoretical activities. Where observational data are required, these are usually at submillimeter and far-infrared wavelengths. Some use may be made of ground-based techniques, such as from the submm/FIR instruments on Mauna Kea. However, as might be expected, most of the spectral range is unobservable from the ground and more often, the needs point to aircraft and balloon platforms, and to small space missions.

B. Discussion of Some Baseline Concepts

While recognizing the usefulness of having a single reference, or 'baseline' concept, the science panel urges that the project not confine itself too narrowly during its "pre phase-A" studies. There are major system trade-offs which have not been fully examined and it may be necessary to maintain two or more baseline concepts at this point. Each concept should be periodically reviewed for its scientific potential.

1. Orbits and Serviceability

One major system-level trade concerns on-orbit serviceability. The present baseline configuration assumes a long lifetime and frequent (bi-annual) manned visits. This scenario assumes a relatively low, circular orbit compatible with the space station. In the "frequent re-visit" configuration, the science instruments could be periodically changed out, and expendibles (such as cryogenes) could be replenished often. Because of the low orbit, the telescope design would have to allow for fast retargeting (every 20 mins or so), and the thermal design must be such that the fast changes in radiative input do not adversely affect the telescope performance. An alternate approach is used on the ESA's FIRST project, which employs a highly elliptic 24-hour orbit and a dewar with a long hold-time.

2. Mission Design

Related to the choice of instruments and orbits is the need to establish a strawman observing sequence. Sky coverage and integration times can affect the choice of orbits. The IRAS mission, which uniformly sampled the sky and had stringent Earth and Sun avoidance angles, was ideally suited to a polar orbit. LDR would also profit from a benign thermal environment, but LDR, unlike IRAS, will carry out primarily pointed observations of galactic, extragalactic, and solar system objects. Also, different scientific experiments have different tolerances for scattered radiation and thermal emission from the telescope. A balance needs to be established between extragalactic surveys, with fairly uniform sky coverage; galactic observations, with sources clustered in a few regions of the sky; and solar system observations, which may place difficult constraints on Sun avoidance angles. A strawman mission, including a representative sample of sources and observing times, will establish the need for thermal stability, frequent slewing, and long integrations.

3. Photometry Requirement

One of the requirements most tightly driving telescope design is that for carrying out short wavelength (50-200 μm) photometry. At issue is how to determine a practical sensitivity limit. There are three fundamental limits: those set by available instruments, those set by natural statistical fluctuations in the thermal emission from the telescope, and those set by "systematic" changes in the temperature and shape of the telescope. The first two are readily defined, and set fundamental sensitivity limits. The third noise source is more difficult to evaluate. It is impacted by many telescope properties: vibration suppression, the number of panels, Earth and Sun avoidance angles, the optical design, the geometry and cycle time of optical choppers, detector stability, cold baffling, etc.

The SCG has been repeatedly called upon to define a photometry requirement, but feels that a more interactive procedure is needed. This one requirement could significantly affect the complexity (cost) of LDR, and should be examined at several different levels against the science pay-off. A sensible requirement could then be set.

Given a photometry requirement, its interpretation in terms of design is not readily apparent. If the telescope were thermally uniform, small vibrations and deformations would not be so serious. Deformations and thermal instabilities could be forgiven with a suitably designed chopper; presumably rapid and involving the secondary, if not the primary. Other issues involve the need for active control of the panels (or their counterparts deeper in the optical path) and of the sunshade design. Also, much might be achieved in the focal-plane instruments themselves, in terms of internal chopping, imagery and instrument stability.

C. LDR Instruments

The NASA sensor technology program is well suited to the development of sensors, loosely defined to be the active elements at far IR and submillimeter wavelengths. The submm program within NASA is commendable and farsighted. The IR sensors program is also fruitful, driven in part by the more immediate SIRTf needs. However, some LDR instrument needs are not adequately met. One example is the need for heterodyne spectrometers.

1. Heterodyne Spectroscopy

Unlike the direct detector spectrometers, heterodyne spectroscopy is not carried out at the observing wavelength, but at a much longer wavelength. New heterodyne spectrometer designs for ground-based applications are being continuously and aggressively developed. However, most ground-based spectrometers have volume, mass, and power requirements which make them unsuitable for LDR use. Also, LDR has specifically identified heterodyne array instruments as essential; straining even the ground-based designs.

2. Update of Focal Plane Design

The SCG, in the period between the Asilomar I and II workshops, made an initial report on the LDR focal plane [2]. In this report, the wavelength coverage and the spectral resolution needs for LDR were transformed into an instrument complement which would satisfy all LDR requirements. Now, an update is

needed to evaluate the weight, power, cryogenic loading, and output data rate. The update should account for technological progress, much of which was presented in the previous section. It should also include a scenario for instrument upgrades.

3. Instrument Changeout

An issue affecting the entire operating philosophy of LDR concerns the practicality of on-orbit changeout of the instruments. The science panel was called upon to define a need, but felt that it had insufficient information. On the one hand, a small package, changed frequently, decreases power, weight, and cryogenic needs, as well as the possible data rate. Also, it allows the more mature instruments to fly first, thereby simplifying the instrument technology program. On the other hand, changeouts are inconvenient and expensive, restrict the choice of orbits, and demand a spacecraft flexible enough to handle the special needs of each payload.

There are several questions which must be answered. Is it practical to change individual instruments, or must the instrument payload be considered as a whole? Can such changeout be considered by unmanned means, or must astronauts be involved? Can a cryogenic system be made suitably flexible to service different instruments? What is the impact of orbit height, inclination, and eccentricity? This issue should be the subject of a special study, possibly in the form of a workshop with the attendance of scientists, instrument and cryogenic engineers, and mission analysts.

4. Multi-Instrument Operation

There will be scientific pressure on the LDR to observe simultaneously with several instruments. This mode of operation provides the most efficient use of the telescope, and eliminates many problems raised with serial observations (due to variations in pointing and gain). Because this mode is important, its impact on the focal plane design needs to be considered. Since the simultaneous use of array imaging with several instruments can have an impact on cryogenic consumption and on data transmission rates, those issues should also be investigated.

The benefit of simultaneous observations can be appreciated from experience with ground-based millimeter telescopes. By observing several transitions and isotopic variants of CO simultaneously it is possible to establish temperatures and densities in interstellar clouds. The same will be true for the hotter, denser regions available at the higher-frequency transitions available to LDR. For example, it will be desirable to observe the [C I] lines at 610 and 370 microns at the same time as the [CII] line at 158 microns, as these lines provide important and complementary information about cloud boundaries.

The observing times necessary for these observations are not likely to be very discordant.

During the Receivers and Cryogenics panel meeting, there was a reassessment of the cryogenic needs. It was apparent that much of the instrument heat load is developed between the leads from cold detector to warm amplifier, and this was an area where improvement could be obtained. To allay the cooling problems, that panel determined that all instruments could be turned off when not in use. However, and this is a point where the science panel voiced strong objections, a serious evaluation of this point is needed.

As was noted in the Asilomar II Workshop on Technology Development Issues ([4], p. 102), the "use of dichroic filters or focal-plane sharing should receive serious investigations for LDR." This technology is becoming increasingly used. From the point of view of observing efficiency, it is just as important to cover frequency space with an array of instruments as it is to cover the focal plane with an array of detectors at single frequencies.

D. Technology Development Recommendations

Panel members were encouraged by the start of a funded NASA technology program, and the group anticipates significant advances in the LDR design. Panel members expressed several concerns about implementation of the technology program. One general concern was how the technology efforts would specifically support LDR needs. The maintenance of a system-level design effort is needed, operating in parallel to the individual technology programs, both for the telescope and for the instrumentation. Also, a clear need was seen for an aggressive science program leading up to the launch of LDR. That effort must involve ground-based and airborne techniques in addition to precursor space missions.

The Science panel feels that a serious study of the photometry requirement is needed. It became clear at the workshop that the same photometric requirement was being independently tackled at several levels in the system. A trade-off study will identify the best way to satisfy the requirement, and may point to the technology(ies) most likely to support photometric science.

An integrated focal plane package should be designed, complete with transfer optics and a cryogenic system serviceable according to LDR mission concepts. New developments in instrument technology might alter the existing strawman payload and some account should be taken of the plans for instrument changeout and for simultaneous operation of instruments.

E. The Pre-LDR Science Program

LDR will be the major, world-class observatory operating in the 30-1000 micron wavelength range. Its design must be on the mark both technically and scientifically. This implies a supported program of submillimeter and far-infrared science and technology. The technology program has been the subject of intensive planning and is now receiving substantial support. The scientific support is less developed, and is clearly needed. Observations are paramount, but some laboratory and theoretical work is also needed.

A scientific program at LDR wavelengths implies astronomical observations, both to learn about the sky and to learn about the operation of instruments at submm/FIR wavelengths. Such a program would certainly lead to modifications of the LDR mission design, which would both enhance its output and increase its reliability. Such an observing program can be approached in two ways: (1) by modest orbital missions; and (2) through whatever wavelength windows are accessible from mountaintops, airplanes, and balloons. A balanced program is clearly the best approach.

Modest orbital missions provide the only access to several vital spectral lines and the only experience with operating LDR-type instruments in space. Operating apertures could be from 1 to 4 meters. Balloons, for short missions, can provide access to most of the LDR wavelengths, and can support a similar range of telescope apertures. Balloons have space-like requirements for instrument weight, power, and hands-off operation. Experience in several programs has demonstrated how balloon instruments have led directly to space application. Airplane-based telescopes can provide more flight opportunities, though with reduced wavelength coverage and with more limited telescope apertures. Hands-on operation makes access easier for scientists and allows for testing of new instruments and techniques, leading to potential devices for space application. Mountaintop observatories can gain only very limited access to the LDR wavelength band, but they provide the only opportunity for science using LDR-like telescope apertures. At relatively low cost, ground-based observations encourage development of the new technologies which are needed for LDR instruments.

Supporting theoretical and laboratory work is also essential to the efficient design of the LDR mission. On the laboratory side, it should be noted that without LDR-motivated support, there is really no incentive to measure the frequencies and strengths of astronomically important spectral lines. Also of concern are certain chemical reaction crosssections directly affecting the predicted abundances of the heavy element hydrides which are vital to the LDR science program. Obtaining laboratory data relevant to LDR is a long-range activity best pursued hand-in-hand with a vigorous theoretical activity.

A steady program of funded theoretical work is also essential to the LDR mission. Where direct observations provide partial information, theoretical models of astronomical sources can help to predict signal strengths for sources and spectral lines otherwise inaccessible. For example, a modest aperture orbital or balloon experiment might yield spectral line strengths in nearby extended sources, but may be inadequate to observe interesting protostellar and extragalactic objects. Theoretical models, including physical and chemical codes in addition to radiative transfer calculations, are essential to help assess the goals for LDR and the design of its instruments.

A balanced pre-LDR science program is vital to LDR. Advance support will sharpen the LDR science objectives, will lead to resolution of several technology challenges, and will improve the LDR mission design.

VI. SUMMARY AND CONCLUSIONS

Rather than repeat the recommendations of the technology and science panels verbatim from the previous two sections, we will attempt in this summary to identify the major issues confronting the LDR project at this time. One theme is particularly apparent, and not unexpected; it is the different perspectives of the science and the technology panels. The Science panel would like to leave some of their options open -- for very good reasons -- and not take a hard stand on all of the functional requirements needed to reach their science goals. The Technical panels, on the other hand, would like specific requirements defined -- again, for very good (but different) reasons -- so they do not spend time developing technology which might not meet the ultimate science needs. This theme is played over many times, and it will be the role of the LDR management to bring the two viewpoints together in a timely manner.

To help further refine our concept of what LDR will be, several outstanding issues must be addressed. The issue of thermal background subtraction in the currently baselined on-axis two-stage optical design is certainly one of the most urgent, since it places fundamental sensitivity limits on the science that LDR can do. In this regard, it is also very important that a detailed photometry specification be developed by the SCG, and that it clearly identify just how steep the scientific slopes are as drivers for aperture size.

A great deal of LDR-directed effort is now being made in the CSTI/PSR program to build space-like telescope structures, utilizing lightweight composite panels and an active precision position control system. Although both erectable and deployable structures are being developed, they may not be dynamically representative of LDR in that they may not be able to take

account of the LDR sunshade. In addition, this effort does not currently include an over-guideline request for an integrated control system.

Although excellent progress is being made in the fabrication and testing of composite panels, detailed functional requirements do not yet exist for their optical, thermal, mechanical, and environmental properties. Unless these are developed, the existing PSR effort may be partially misdirected. The LDR program must do all that it can to provide guidance for this very important NASA program.

In a similar vein, it is important that a systems-level error tree be developed for LDR. Until this is done, it will be impossible for the different technology disciplines to understand their own goals, let alone the impact they might have in other areas. Implicit in this are two requirements: the need for realistic modeling/simulation capabilities in all disciplines, and the need for an interdisciplinary systems-level design team. The systems-level approach to specifications for LDR was called for by all panels.

In the area of science instruments, good progress is being made -- in some cases, beyond what would have reasonably been expected a few years ago. Specific recommendations have been made for both heterodyne and direct detector development. Methods to reduce heat loads or increase operating temperatures remain a primary concern. In addition, the instrument complement requires redefinition, as does its heat load.

Progress is already being made on many of the issues raised in this report. With adequate funding, good progress should be possible in all areas. If a single recommendation were to be made, it would be the need to revisit, using a systems-level approach, both the science and technical requirements for LDR.

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